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Continental deformation accommodated by non-rigid passive bookshelf faulting: An example from the Cenozoic tectonic development of northern Tibet

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ABSTRACT

Collision-induced continental deformation commonly involves complex interactions between strike-slip faulting and off-fault deformation, yet this relationship has rarely been quantified. In northern Tibet, Cenozoic deformation is expressed by the development of the >1000-km-long east-striking left-slip Kunlun, Qinling, and Haiyuan faults. Each have a maximum slip in the central fault segment exceeding 10s to ~100 km but a much smaller slip magnitude (~<10% of the maximum slip) at their terminations. The along-strike variation of fault offsets and pervasive off-fault deformation create a strain pattern that departs from the expectations of the classic plate-like rigid-body motion and flow-like distributed deformation end-member models for continental tectonics. Here we propose a non-rigid bookshelf-fault model for the Cenozoic tectonic development of northern Tibet. Our model, quantitatively relating discrete left-slip faulting to distributed off-fault deformation during regional clockwise rotation, explains several puzzling features, including the: (1) clockwise rotation of east-striking left-slip faults against the northeast-striking left-slip Altyn Tagh fault along the northwestern margin of the Tibetan Plateau, (2) alternating fault-parallel extension and shortening in the off-fault regions, and (3) eastward-tapering map-view geometries of the Qimen Tagh, Qaidam, and Qilian Shan thrust belts that link with the three major left-slip faults in northern Tibet. We refer to this specific non-rigid bookshelf-fault system as a passive bookshelf-fault system because the rotating bookshelf panels are detached from the rigid bounding domains. As a consequence, the wallrock of the strike-slip faults deforms to accommodate both the clockwise rotation of the left-slip faults and off-fault strain that arises at the fault ends. An important implication of our model is that the style and magnitude of Cenozoic deformation in northern Tibet vary considerably in the east–west direction. Thus, any single north–south cross section and its kinematic reconstruction through the region do not properly quantify the complex deformational processes of plateau formation.

1. Introduction

The fundamental mode of continental tectonics has been characterized by two end-member processes: plate-like rigid-body motion (e.g., Tapponnier et al., 1982; Weldon and Humphreys, 1986; Avouac and Tapponnier, 1993; Meade, 2007) and distributed deformation via viscous flow (e.g., England and Houseman, 1986; Yin and Taylor, 2011). In the rigid-plate model, continental deformation is quantified by rigid block rotation on a sphere about their respective Euler poles; the horizontal dimension of the blocks is much greater than the width of faults/shear zones that bound the blocks (e.g., Avouac and Tapponnier, 1993). In contrast, the viscous-flow model quantifies continental deformation by solving a boundary-value problem that requires the knowledge of lithospheric rheology (e.g., England and Houseman, 1986). This model envisions distributed continental deformation, with major faults approximated as zones of high strain within a continuum. These two end-member models have been extensively tested in Tibet against structures created during the Cenozoic India–Eurasia collision (e.g., Yin and Harrison, 2000; Zhu et al., 2005; Yin, 2010a; van Hinsbergen et al., 2011; Yin and Taylor, 2011). Debates have been centered on whether the >1000-km-long east-striking left-slip Haiyuan, Qinling, and Kunlun faults in northern Tibet (Fig. 1) have acted as rigid-block boundaries (Tapponnier et al., 1982; Avouac and Tapponnier, 1993; Tapponnier et al., 2001) or transfer-fault structures linking dip-slip fault systems (e.g., Burchfiel et al., 1991; Yin, 2000; Duvall and Clark, 2010).

One form of rigid-block models for deformation in northern Tibet is bookshelf faulting, which requires that the observed left-slip faulting is driven by regional right-lateral shear (Cobbold and Davy, 1988; England and Molnar, 1990). Applying the classic rigid

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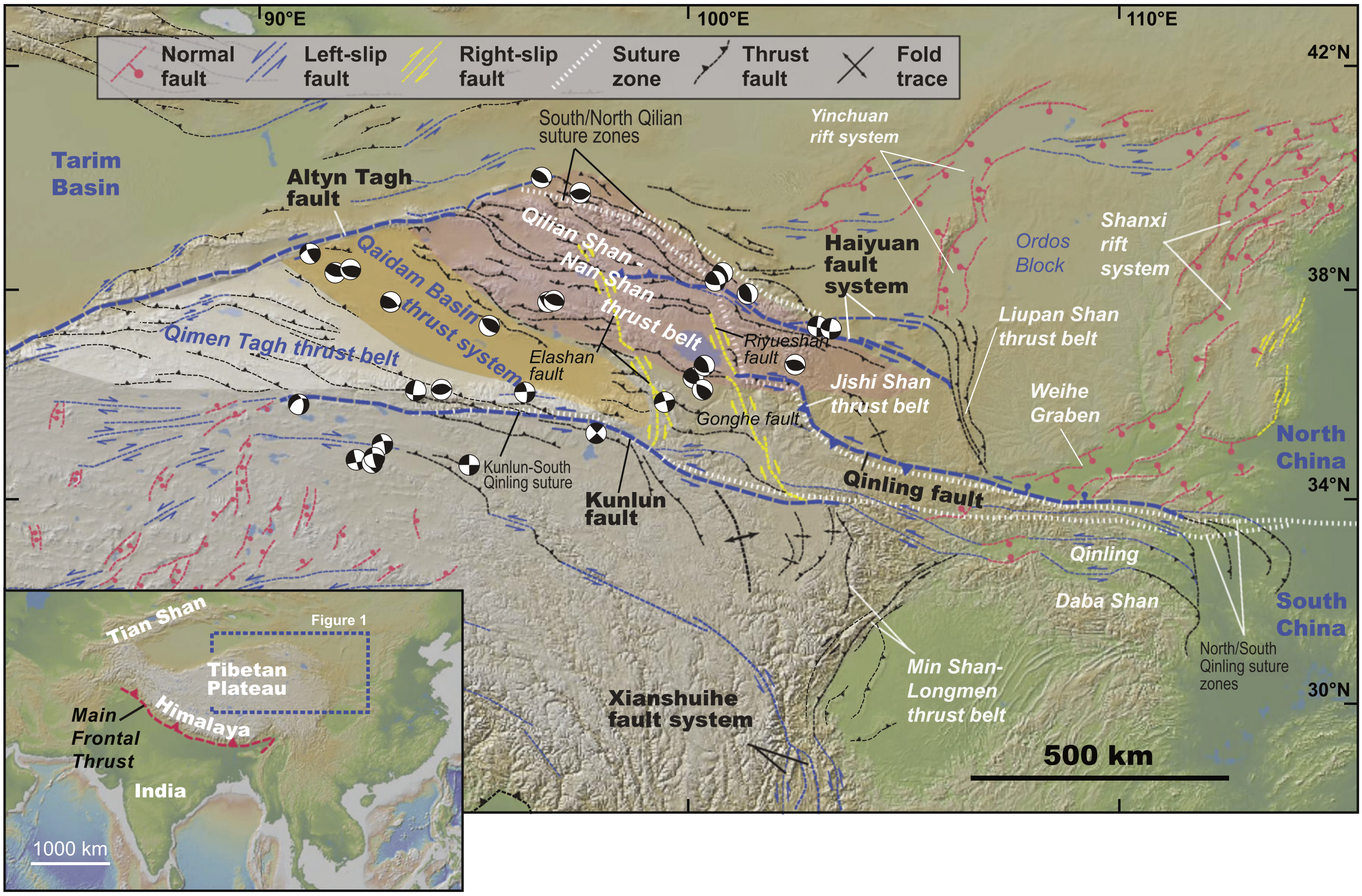

Fig. 1. Color-shaded relief map showing Cenozoic faults related to the India–Eurasia collision zone after Yin et al. (2008a); Taylor and Yin (2009), and Zuza et al. (2016). Also shown are Harvard centroid moment tensor (CMT) earthquake focal mechanisms from 1 January 1977 to 1 January 2009 of events >M5.5. Inset shows location of northern Tibet in the context of the Himalayan–Tibetan orogen. The digital topographic basemap is from the GeoMapApp software (Ryan et al., 2009) available at http://www.geomapapp.org/.

bookshelf-fault model (Freund, 1970) to explain the tectonic development of northern Tibet raises several important questions that have not yet been addressed: (1) Why do the parallel east-striking left-slip faults terminate at the northeast-striking left-slip Altyn Tagh fault rather than a right-slip northeast-striking shear zone as required by the bookshelf-fault model (Fig. 1)? (2) How are the required lithospheric-scale "gaps" and "overlaps" at the ends of the rotating blocks accommodated by off-strike-slip-fault deformation (e.g., Luyendyk et al., 1980; Onderdonk, 2005; Platt and Becker, 2013) (Fig. 2)? (3) What is the kinematic relationship between the east-striking left-slip faults and the triangular eastward-tapering thrust belts at the western ends of the strike-slip faults (i.e., the Qimen Tagh, Qaidam, and Qilian Shan-Nan Shan thrust belts) (Fig. 1)?

In this study we propose a non-rigid bookshelf-fault model (e.g., Yin and Pappalardo, 2015) to resolve the above issues. Specifically, we show that an eastward decrease in Cenozoic strain results in clockwise rotation and left-slip bookshelf faulting across northern Tibet. The detached rotation of these bookshelf faults against rigid bounding domains, a process which we refer to as passive bookshelf faulting, may explain why a left-slip bookshelf fault system is bounded by the left-slip Altyn Tagh fault (Fig. 1). Non-rigid wallrock deformation within the strike-slip-fault-bounded regions accommodates both the clockwise rotation of the strike-slip faults and the space issues that arise at the ends of the bookshelf panels. The model implies that thrust belt development and strike-slip faulting in the region are coeval and kinematically linked, which contrasts an earlier suggestion that they represent two distinct stages of plateau development (e.g., Yuan et al., 2013).

2. Cenozoic left-slip faults in northern Tibet

The ~N110°E-striking left-slip Kunlun, Qinling, and Haiyuan faults, extending for ~1500, ~1000, and ~1000 km respectively, are by far the longest and most continuous structures in northern Tibet (Fig. 1) (Tapponnier et al., 2001; Taylor and Yin, 2009). The faults are lithospheric structures (Wang et al., 2011; Gao et al., 2013) that closely follow the surface traces of the Paleozoic and Mesozoic Qilian, Qinling, and Kunlun suture zones (Yin and Harrison, 2000; Wu et al., in press) (Fig. 1).

The kinematics of these major east-striking faults has been related to lateral extrusion (Tapponnier et al., 1982, 2001; Cheng et al., 2015), strain transfer between thrust belts (Burchfiel et al., 1991; Zhang et al., 1991; Duvall and Clark, 2010), and bookshelf faulting associated with clockwise fault rotation induced by broad and distributed north-trending right-lateral shear (England and Molnar, 1990; Zuza and Yin, 2013) (Fig. 3**a**). The extrusion fault model requires high slip rates (>10–20 mm/yr), large fault offsets (100s km) (Tapponnier et al., 1982; Avouac and Tapponnier, 1993), the presence of zipper thrusts at the western end of the left-slip faults (Peltzer and Tapponnier, 1988; Cheng et al., 2015), and a conjugate and coeval right-slip fault with a similar slip magnitude to assist eastward lateral extrusion (scenario 1 in Fig. 3**a**). In contrast, the transfer-fault model predicts transpressional deformation at the termination thrusts oriented obliquely to the strike-slip faults (scenario 2 in Fig. 3**a**). Finally, the bookshelf fault model predicts clockwise rotation of both the left-slip faults and the fault-bounded wallrock. If the bookshelf panels are rigid, the model predicts the formation of "gaps" and/or "overlaps" at the end of the rotating blocks (scenario 3 in Fig. 3**a**); these gaps and overlaps can be reconciled